480Mbps / 1 Gbps radio-over-fiber link based on a directly modulated III-V-on-Silicon DFB laser

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***Abstract*—In this work we characterize the RF modulation characteristics and the dynamic range of a III-V-on-Silicon DFB laser. The direct modulation of this laser is demonstrated with a 1Gbps radio-over-fiber link at a carrier frequency up to 24 GHz using QPSK modulation. 480Mbps 64-QAM transmission at 3.5 GHz carrier frequency is demonstrated as well. In the 480 Mbps experiment both the transmitter and receiver are silicon photonic components, providing a SFDR of about 90 dBHz$^{2/3}$ for the complete optical link including receiver electronics as well.**

Keywords—Silicon photonics; Optical fiber communication; Microwave photonics; Quantum well lasers.

I. Introduction

The goals for next generation mobile networks (5G) are very ambitious and achieving both spatial and spectral densification will be vital [1][2]. Spectral densification can happen by either opening up currently sparsely used bands, such as the 3.5 GHz band or moving to higher frequencies such as the 24, 28 or 60 GHz bands. Spatial densification can be realized by the use of cloud radio access network (C-RAN) architectures, where a central office services and coordinates several pico-cells. A key enabler for the deployment of pico-cells is the radio-over-fiber link (RoF). RoF allows moving complex operations to generate and process the wireless signal to the central office, thereby keeping the cost of the remote antenna heads low.

Analogue links put a stringent requirement on the linearity of the used components. Therefore in most cases external modulation is preferred in radio over fiber links. However, directly modulated lasers have proven a viable alternative and have gained interest over the past years [3], given the compactness of the resulting solution. The realization of compact transceivers is of paramount importance for such C-RAN architectures, considering the large number of pico-cells that needs to be addressed. Implementation of these transceivers on a silicon photonic platform is particularly attractive, as this integration platform allows the dense integration of high-speed optical functions at low cost. Recently a directly modulated III-V-on-silicon laser been demonstrated for digital links over several kilometers of fiber [4]. This type of laser can be co-integrated with passive optical functions such as wavelength multiplexing functionality and integrated high-speed photodetectors. The integration on silicon also enables close integration with electronics.

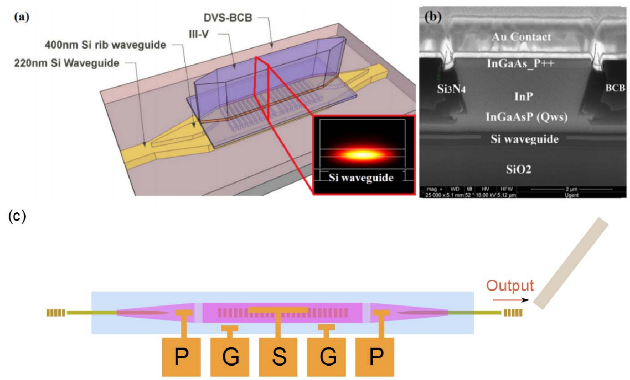

Figure 1: (a) A 3D representation of the III-V-on-Silicon DFB laser; (b) SEM cross-section of the laser; (c) Top view with schematic of the electrical and optical interface.

In the first part of this paper, a RoF link based on silicon photonic components will be demonstrated in the 3.5 GHz band, as this band can be of interest in future networks both for distributed antenna systems as well as for small cell architectures. On the transmitter side a linear directly modulated III-V-on-Silicon DFB laser is used. On the receiver side a Germanium-on-silicon waveguide-coupled photodiode with co-integrated transimpedance amplifier is used [5]. 480 Mpbs data transmission, using a 64-QAM modulation scheme is demonstrated. Next, 1 Gbps data transmission is demonstrated at carrier frequencies of 3.5 GHz, 20 GHz and 24 GHz using a QPSK modulation format. More complex modulation schemes considered for 5G applications will be tested in the near future.

The remainder of this work is structured as follows. In section II the RoF transmitter based on a III-V-on-silicon DFB laser is described in detail. In section III the 480 Mbps RoF link based on this transmitter and a silicon photonic receiver is demonstrated. In section IV a 1 Gbps RoF data link with the III-V-on-silicon laser transmitter is discussed. Finally section V summarizes the conclusions.

II. Silicon Photonic Transmitter

A directly modulated III-V-on-silicon distributed feedback laser is used as transmitter in this work. This laser is manufactured on a silicon-on-insulator PIC containing passive waveguides, the distributed feedback grating and vertical fiber coupling gratings, as shown in Fig. 1. The gain section of the laser is integrated by adhesive die-to-wafer bonding of a multi-quantum well InP-based layer stack on the silicon PIC. This wafer bonding is achieved using a 10 nm thick polymer (DVS-BCB) layer. A more detailed description of the device fabrication can be found in [6]. In Fig. 2(a) the LI curve and IV curve of the laser are shown, at 20°C. The laser is 400 µm long. The threshold current of the laser is approximately 20 mA and the series resistance is 7 Ω. At an injection current of 100 mA the output of the laser reaches 3 mW at a wavelength of 1570 nm. The laser output is single mode with a side mode suppression ratio of 40 dB. The small signal modulation bandwidth of the laser was determined using a Keysight PNA-X 67 GHz network analyzer. The laser was contacted using a 40 GHz bandwidth GSG RF probe. The S_{21} parameter for different injection currents is shown in Fig. 2(b). The bandwidth increases with increasing injection current due to a shift of the relaxation oscillation resonance. At an injection current of 100 mA the 3 dB bandwidth rises to 15 GHz, followed by a slow roll off. In this specific design the III-V-to-silicon tapers were electrically isolated from the laser section and can be pumped separately. This was found to improve the performance of the device.

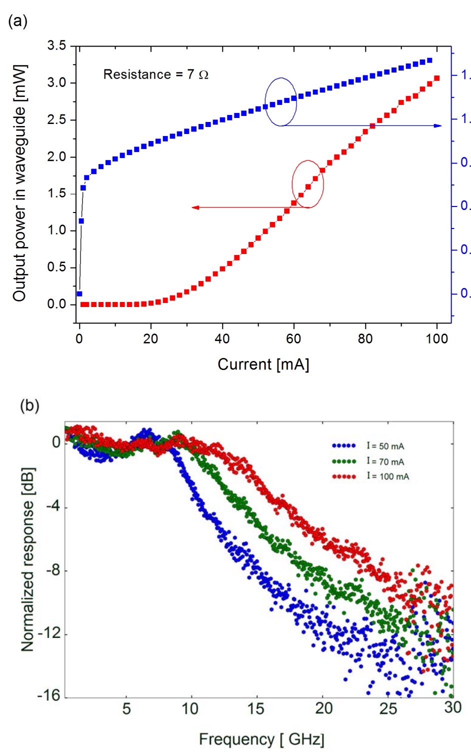

Figure 2: (a) III-V-on-silicon DFB laser LI and IV curve; (b) S_{21} small signal modulation transfer function.

III. 64-QAM 480 Mbps transmission

As a first demonstration a 5 km RoF link using a 64-QAM signal on a 3.5 GHz carrier was realized. The layout of the set-up is shown in Fig. 3. The III-V-on-silicon DFB was directly modulated using an Anritsu MS2692A signal generator. A SHF RF amplifier with 50 GHz bandwidth was placed between the signal generator and DFB laser to increase the modulation depth of the laser as the on-chip laser was not impedance matched. The light from the on-chip laser was collected by a cleaved SMF fiber using a vertical grating coupler. The optical power in the fiber was -3 dBm and the fiber coupling losses are estimated at 7 dB. The ouput was amplified with a Keopsys EDFA to 10 dBm optical power, after which a Santec tunable optical filter (OTF-350) was used to filter out the ASE generated from the EDFA. An optical power of 6 dBm was coupled into the receiver PIC again using a cleaved SMF and a vertical grating coupler. The optical power at the photodiode was estimated to be -3 dBm due to the grating coupler losses. A linear TIA [7] was integrated with the silicon receiver PIC using wire bonding and connected to an Anritsu signal analyzer used to demodulate the signal and determine the error vector magnitude (EVM).

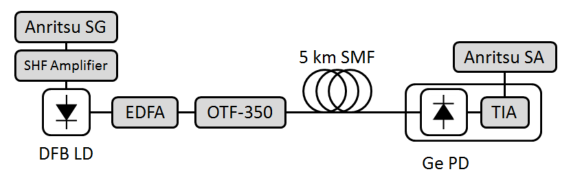

Figure 3 : Measurement set-up used for the 480 Mbps 64-QAM RoF transmission.

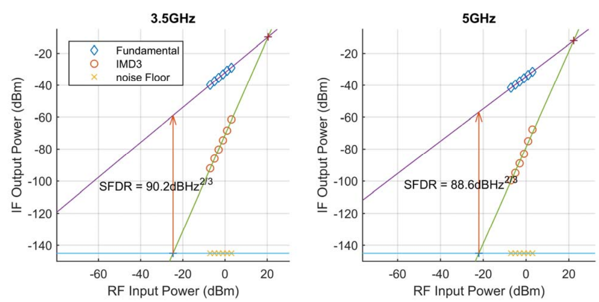

Figure 4: Dynamic range measurement of the entire optical link at a carrier frequency of 3.5 GHz and 5 GHz.

A linearity measurement of the entire link is shown in Fig. 4. A SFDR of 90 $dBHz^{2/3}$, for a carrier frequency of 3.5 GHz and a laser bias current of 100 mA, is obtained. It was found that the linearity of the link depended strongly on the DC injection current of the DFB laser. This can be explained by the location of the relaxation oscillation resonance peak in the frequency response of the laser, which shifts to higher frequencies with increasing bias current. It is well-known that for the sake of linearity it is beneficial to work at a carrier frequency far away from this laser resonance frequency. We also measured the linearity at 5 GHz and found a similar SFDR. The IIP3 of the link is approximately 20 dBm. Fig. 5(a) shows the constellation diagram of a 480Mbps 64-QAM signal transmitted over 5 km of single mode fiber. The measured rms error vector magnitude was 3.3 percent, showing good signal quality and promising performance.

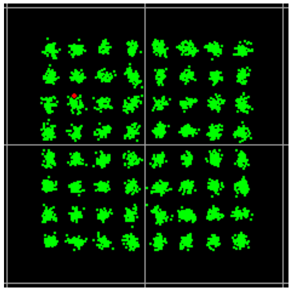

Figure 5: Constellation diagram of the 64 – QAM measurement.

IV. 1GBPS QPSK TRANSMISSION AT 3.5 GHZ, 20 GHZ AND 24 GHZ CARRIER FREQUENCY

In a second demonstration a RoF link was set up using a 1 Gbps QPSK signal at different RF carrier frequencies. To achieve these higher data rates and higher carrier frequencies, an arbitrary waveform generator (AWG) and Keysight real-time DSOZ634A Oscilloscope with 63 GHz bandwidth was used instead of the Anritsu signal generator and analyzer. The setup is shown in Figure 6.

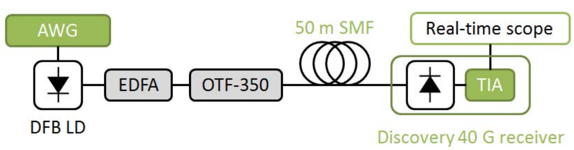

Figure 6: Measurement set-up of the 1 Gbps RoF link.

The silicon photonic receiver was replaced by a Discovery photodiode with TIA, as the bandwidth of the available silicon photonic receiver was limited to 7 GHz. To focus on the signal quality as function of carrier frequency the 5 km single mode fiber was replaced with 50 m of single mode fiber. In a first experiment 1 Gbps QPSK at a carrier frequency of 3.5 GHz was transmitted. The constellation diagram and spectrum of the 1 Gbps QPSK signal can be seen in Fig. 7(top-left) and 7(top-right) respectively. The measurement showed an rms EVM of 3.4 percent, comparable to the 64-QAM constellation measurement of section III.

The carrier frequency was then increased to 20 GHz on which again a 1 Gbps QPSK signal was modulated, while maintaining the same RF input power. The rms EVM degraded to 11.5 percent (see Fig. 7(bottom-left)), which is still very good for QPSK. However if we increase the carrier frequency to 24 GHz the rms EVM degrades to 20.5 percent (see Fig. 7(bottom-right)). This can be expected as the laser is operated beyond its modulation bandwidth and the modulation efficiency decreases quickly. However, this rms EVM is still corresponding a BER below 10^{-5}, which allows for forward error correction with limited overhead.

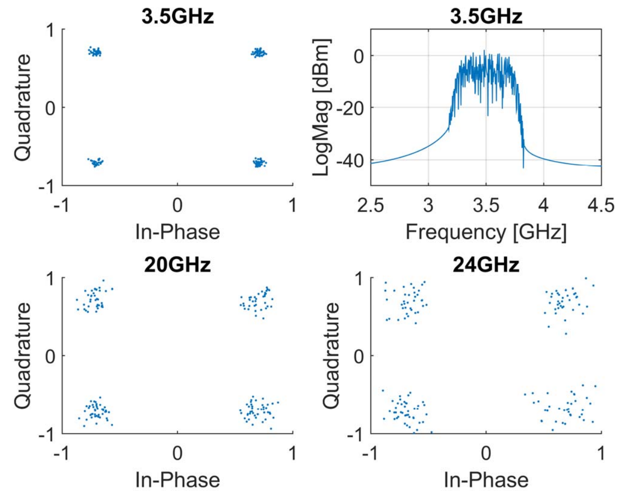

Figure 7: Top left: QPSK constellation plot of the received RoF signal at a carrier frequency of 3.5 GHz; Top right: spectrum at the signal analyzer; Bottom left: constellation diagram at 20 GHz carrier frequency; Bottom right: constellation diagram at 24 GHz carrier frequency.

V. CONCLUSION

For the first time, a RoF link based on a directly modulated III-V-on-Silicon DFB laser and a Germanium-on-Silicon waveguide-coupled photodiode is demonstrated. 480 Mbps 64-QAM data transmission over 5 km single mode fiber on a 3.5 GHz carrier is demonstrated. The use of silicon photonic components enables low-cost and densely integrated radio-over-fiber transceivers, which will be essential for the realization of 5G cloud radio access networks (C-RANs) and distributed antenna systems. The possibility to achieve higher carrier frequencies and data rates is investigated as well, up to a carrier frequency of 24 GHz and a data rate of 1 Gbps. While beyond 10 GHz a commercial III-V receiver was used, recently silicon photonics based receivers with a small-signal bandwidth beyond 67 GHz have been demonstrated [8], as well as III-V-on-silicon DFB lasers with a small-signal modulation bandwidth beyond 27 GHz [9], making mm-wave radio-over-fiber transceivers/links based on silicon photonic components possible.

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